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Performance Assessment of a Multi-Step Oscillating-blade Vertical Wind Turbine

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(Abstract) A vertical axis wind turbine like the Savonius turbine can develop relatively high torque at small rotational speeds, but they harness a small fraction of the wind incident upon it. The Savonius rotor rotates by an action of differential drag which makes it less efficient. One idea, which is introduced in this work, is to render a vertical rotor rotates by an absolute positive drag in order to influence significantly the generated torque and power coefficient. So, in this study, a rotor is proposed which comprises four vertically arranged (steps) stages and at each step there are two (flat) rectangular blades aligned at 180-degree angle around a vertical shaft in the same vertical plane. Geometrically, the four vertical planes which enclose the blades in the four steps make a 45 degree-angle with each other, successively, from the topmost step to the bottommost step. A total of eight blades two at each step forms the basic configuration of the rotor. The blades open automatically as a result of the air pressure when they advance into the wind (and hence experience zero negative drag), but close (again automatically) when retreating from the wind, i.e., during the power-harnessing part of the operating cycle. When the flat blade closes it is exactly in a vertical plane receiving air flow and when it opens it is exactly in a horizontal plane not receiving air flow at all. Theoretical and experimental dynamic torque and power harnessing tests were carried out for the 8-blade rotor. But, theoretical predictions were carried out for rotors modified with 4 blades or subsequently 16 blades and having the same height of the 8-blade rotor. Other theoretical predictions were made for the 4- and 16-blade rotors with the overall dimensions of the blade kept constant, i.e., duplication of the number of blades means duplication of the rotor height. The results, in terms of torque and power coefficients, indicate that the proposed type of turbines is very competitive to a Savonius wind turbine. It provides the power coefficient higher than that of the classical Savonius rotor while the Savonius rotor offers larger speed ratios for operation. Also, the Savonius rotor provides its maximum power coefficient, which is lower than that of the proposed rotor, at a higher speed ratio than that of the proposed rotor.

Keywords: Wind Energy; Oscillating-blade Rotor; Savonius Turbine; Multi-Stage Rotor; Theoretical Analysis; Experimentation

1. INTRODUCTION

It has become true that achieving sustainable energy means using natural energy effectively. Wind turbine is a device to change wind energy into mechanical energy. These turbines are classified into two categories, horizontal and vertical axes. The horizontal axis wind turbines have complicated structures and are economically valuable only in areas where the permanent winds and high speeds are available and are mainly employed for generating electricity. Advantages of wind turbines have been thoroughly discussed in the literature [1]. Particularly, advantages of the Vertical Axis Wind Turbines (VAWTs) which can be summarized as follows: (i) the simple design due to the capability of capturing air from any direction, (ii) the generator and the gear can be fixed to ground, and (iii) the small workspace.

The VAWTs such as Savonius turbines have a simple structure and are capable to operate at low wind speed [2]. The basic idea of vertical axis wind turbines came after an early design made by Savonius, 1931 [3]. Unlike horizontal axis turbines, in vertical axis turbines, the rotation speed is low and torque is high. These turbines are independent of the wind direction. In vertical axis wind turbines such as Savonius rotating axis is perpendicular to the wind direction. Therefore the surface which is moved by air, after rotating half a round, should move in reverse direction of wind. This is the reason for power ratio reduction.

One of the promising research directions in wind power engineering is the development of wind-driven facilities

with a wind turbine of the Darrieus rotor type [4,5]. Wind turbines of this type are substantially different from the traditional propeller-driven wind turbines, have a vertical axis of revolution, and can operate with all directions of the wind, i.e., no stream-wise orientation of the system is required. Savonius type vertical axis turbine produce higher torque and have lower cut-in speed. A lift type Darrieus turbine (classified as vertical axis) can have blade tip speed many times the speed of the water current (i.e. the Tip Speed Ratio (TSR) is greater than 1). Hence a Darrieus turbine generates less torque than a Savonius but it rotates much faster. This makes Darrieus turbines much better suited to electricity generation, regardless of the direction of flow of the flowing bodies like water or wind. Darrieus type turbine has weak self starting characteristics and higher cut-in speed. A Savonius drag type turbine can be combined to a Darrieus turbine to overcome its weak self starting characteristics [6].

Too many studies regarding the power, speed, torque and aerodynamics of VAWT systems are cited in the recent review articles [7-9]. The amount of energy that can be extracted from the wind has a theoretical maximum of about 60%, which is known as the Betz Limit. Modern wind turbines are close to this limit over a range of wind speeds. Of course the wind does not blow at the best speed all of the time. On average the wind turbine produces 35% of the electricity it could produce over a year at maximum output. A computational study was introduced for optimizing the airfoil cross-section of a VAWT [10]. The main design constraints such as the tip speed ratio, solidity and blade profile were considered to enhance the generated torque. Such study was important because it introduced the first step towards the development of the VAWT utilizing an optimized blade cross-section. The authors suggested further research and development in such field. An experimental study of Savonius turbines with different overlap ratios and shift angles under different wind speeds was performed in [11]. The results showed that a higher overlap ratio has an effect on improving the starting characteristics of the Savonius turbine than any phase shift angle changes. The power coefficient is found to be significantly increased at a specific phase shift angle at a specific air velocity. A twisted blade was a simple method to reduce the negative torque and the self-starting characteristics in a three bladed rotor system of Savonius turbine [12,13]. The experiments were performed at a low speed wind tunnel on the basis of starting torque, power output and rotational speed. The investigation showed higher performance of the twisted bladed rotor compared with that of the conventional semicircular bladed rotor. The measurements also indicated that there is an optimized twisted angle. Artificial neural networks corresponding to different available experimental data on six blades with different wind speed were done in [14,15]. The power coefficient was obtained at different angles of blade in proportion to blowing wind in a complete rotation. A comparison of the obtained results with the corresponding experiments showed that the simulation is able to provide reasonable computations for the maximum power of rotors and maximizing the efficiency of Savonius wind turbines. It was also found that, increasing the tip speed ratio leads to a higher power ratio and torque.

An effort for improving the power coefficient of the conventional and modified Savonius rotors with and without central shaft was done [16]. The results of modified Savonius rotor with the central shaft satisfied a maximum power coefficient of 0.32. Multi-bladed and multi-stage (multi-S) Savonius rotors for capturing and storing wind energy were developed and tested in [16,17]. A solution for the wind and load fluctuation problems was suggested. The power coefficients of the new multi-S as well as the standard Savonius rotors were presented in view of the measurements and new theoretical analysis [18]. A new geometrical parameter was found to play an important role in improving the performance of the turbine. Effects of guide plates with either flat or curved forms shielding the returning blade were optimized [19]. A relative increase of the power coefficient was registered in that research with the highest performance satisfied by the curved plate. An experimental and computational analysis of a micro wind turbine for urban environment was presented in [20]. The results of these researches showed that VAWT provide operational abilities at lower speeds at which the horizontal Axis Wind Turbines (HAWT) do not have a practical application due to high wind speed requirement.

Experimental and two-dimensional CFD studies, using Fluent 6.2 software, were introduced in [21] on an airfoil shaped two bladed H-Darrieus rotor. A comparative study between experimental and computational works was carried out and found to be quite encouraging. More attentions are recently directed to the straight-bladed vertical axis wind turbine (SB-VAWT) because of its simplicity of construction and low costs [22,23]. To improve the performance, the cycloidal blade system and the individual active blade control system were adopted. Aerodynamic analysis is carried out for cycloidal wind turbine by changing the pitch and phase angles based on the cycloidal motion according to the change of wind speed and wind direction. It was found that the generated electrical power is about 30% higher than wind turbines which use fixed pitch angle configuration. Additionally, aerodynamic analysis showed performance improvements of 60% as reported in [24]. However, the starting performance of the straight-bladed vertical axis wind turbine (SB-VAWT) was found to be poor by investigators in [21]. Alternatively, Savonius rotor was combined to the SB-VAWT in order to increase its starting torque since the Savonius rotor has much better starting torque characteristics. The simulation results in [21] showed that the starting and dynamic torque measures of the hybrid Savonius-SB-VAWT have been improved.

Some rotor designs have sought to eliminate the negative drag that acts on the blades acting upwind in a Savonius rotor [25,26]. Usually, they implement slatted or swinging blades that are designed to trap wind during their downwind travel. But swing freely in order to eliminate negative drag during their upwind travel. Dynamic-torque tests [25] were performed for a Savonius wind rotor with hinged blades to improve the performance of the slatted-blade rotor that was originally proposed in [26]. This design provided slightly higher torque than the classical Savonius design at low wind speeds, but it reaches only a maximum of 0.05 power coefficient, compared to 0.18 for a typical Savonius turbine.
In this article, an on-off blade vertical wind turbine is theoretically and experimentally investigated. It looks like a vertical tower of four (steps) stories where each story has a circular floor and a circular roof. The detailed design is presented in Section 2 and its experimental set up is explained in Section 3. Theoretical and experimental results are presented and discussed in Section 4 and conclusions are extracted in Section 5.

2. TURBINE DESIGN CONSIDERATIONS

2.1 Rotor Design

The schematic diagram of the proposed multi-step on-off blade vertical wind turbine is shown in **Figure 1**. It comprises four vertically arranged (steps) stages. Five circular end plates, installed to a vertical shaft, are used to separate the (steps) stages from each other such that each stage is formed by one upper end plate and one lower end plate. In each stage there is one advancing blade of squared shape and one returning blade of the same shape and dimensions and both are lying in the same vertical plane, i.e., They are aligned such that they make a 180-angle away from each other, see **Figure 2**. The four vertical planes of blades in the four steps are spatially arranged such that they make a 45^0-angle with each other successively from the top step to the bottom one as indicated in **Figure 3**.

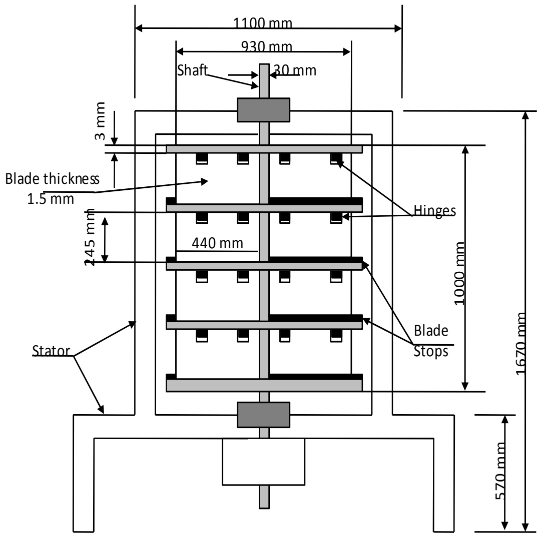

Figure 1 Schematics of the proposed on-off blade turbine.

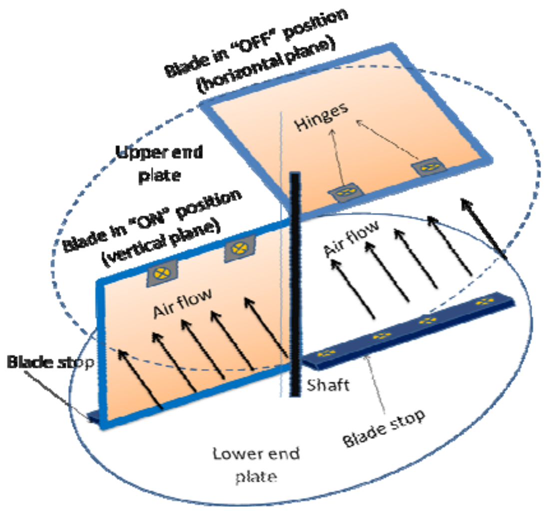

Figure 2 Configuration of blades during operation.

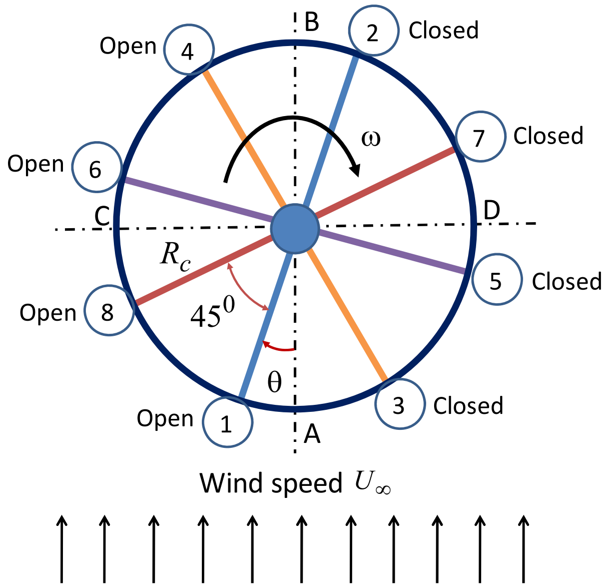

Figure 3 An instantaneous top view of the proposed rotor.

During operation, when every two blades in the same (step) stage are perpendicular to the flow of air, one of them will be totally open and the other one will be totally closed. The "on" position means that the blade is totally closed for receiving air and the "off" position means that the blade is not receiving air at all and opened. In other words, each blade in every step is totally open along a180-degree angle of operation and is totally closed along the other 180-degree angle of operation. Hinges are used to install the on-off blades in each step to their upper endplate. Blade stops in each step are installed to their lower endplate. The blade stops keep the blades exactly in a vertical plane during its

"on" position which consumes a 180-degree, active angle of operation. At the end of the active angle of operation the blade is opened (turned) off by the action of the air pushing it back to settle in a horizontal plane and it stays in this off position for a 180-degree inactive angle of operation. With hinges and blade stops used as shown in **Figure 2**, the on-off positions of the blades are performed by the action of air flow itself. In the schematic top-view diagram shown in **Figure 3**, it is obvious that there are only four active blades which are in the "on" positions at any moment of operation. The other four blades are totally (opened) switched off and are not receiving air at all. So, according to **Figure 3**, blades 1 and 2 are in the topmost step, and all the time of operation we will have one of them active and the other will be inactive. Same thing goes for blades 3 and 4 in the second step, blades 5 and 6 in the third step and blades 7 and 8 in the (fourth) bottommost step. Also from **Figure 3**, the axis AB is the axis at which blades begin to switch "on" and "off" because it is parallel to the direction of air flow. The "on" position is obtained at point A and the "off" position is obtained at Point B. The axis CD represents the position at which the projected area of any open blade will equal the real area of the blade itself. Unlike Savonius rotors which rotate by an action of differential drag, our proposed design configuration makes the rotor rotates by an absolute positive drag. The important dimensions of the stator and rotor are shown in **Figure 1**. These dimensions are the ones which were used to make the experimental setup.

2.2 Power Calculation

In the present theoretical analysis, the air is assumed to be irrotational at any instant and it remains irrotational thereafter. Of course, the assumption of zero viscosity, and the absence of boundary layer effects, is never perfectly correct, and it's obviously possible to introduce or remove vorticity due to real-world boundary layer effects. However, in a large class of realistic situations the assumption of irrotational flow is valid [12]. Under these conditions there exists a momentum force created by the velocity component normal to blades which is $U_\infty \sin\theta$. Because of the blade rotation with angular velocity ω, the relative velocity is considered in the computation of the momentum force acting on one blade as follows, see **Figure 3**:

$$F = \rho R_c L (U_\infty \sin\theta - \omega R_c / 2)^2 \qquad (1)$$

where L is the height of the blade and R_c is the length of the blade. The instantaneous generated torque and power coefficients, of a blade are then computed from:

$$Torque = F \times R_c / 2 = 0.5 \rho R_c^2 L (U_\infty \sin\theta - \omega R_c / 2)^2 \qquad (2)$$

$$C_p = \frac{Torque \times \omega}{\rho U_\infty^2 R_c L} = \frac{0.5 \rho R_c^2 L (U_\infty \sin\theta - \omega R_c / 2)^2 \times \omega}{\rho U_\infty^2 R_c L} \qquad (3)$$

Introducing the definition of the speed ratio λ, that reads:

$$\omega = \omega R_c / U_\infty$$

The power coefficient of the blade can be then rewritten in the following form

$$C_p = \frac{1}{2} \lambda \left(\frac{\lambda^2}{4} - \lambda \sin\theta + \sin^2\theta \right) \qquad (5)$$

The instantaneous total torque and power coefficients can be computed by summing the contributions made by the instantaneously four active blades in the different four steps. Referring to **Figure 3**, and at any moment of operation, there are only four active blades which receive air one in each step. The mean value can simply be computed by integration over the active angle of operation from $\theta = 0$ to $\theta = \pi$.

3. TURBINE EXPERIMENTATION

The experimental setup of the proposed on-off blade rotor is shown in **Figure 4**. It is in the form of two main parts. The first part is the stator part which consists of the supporting base and the carrying frame. The other part is the (rotor) dynamic part which consists of a 30-mm diameter shaft with five circular endplates fixed to it. The five circular endplates are of equal dimensions. Every two endplates enclose one step with two blades aligned at a 180-degree angle around the shaft. The four steps are of the same height and the eight blades are of equal dimensions. **Figure 4** reveals the philosophy of operation of the suggested rotor in which only four active blades receive air at any moment of operation with the other four blades switched off as explained before.

Figure 4 View of the experimental test rig.

Precautions were made in manufacturing and assembling of the rotating parts of the turbine for avoiding the effects of misalignment and unbalance. The paddles are hinged to the upper endplates in their own steps. A maximum of 90-degree angle of blade openings are achieved by using blade stops fixed to the lower endplate in their own steps. The shaft is supported by two types of bearing: thrust bearing joined to the supporting base near its bottom and radial bearing joined to the carrying frame near its top. It is also noted that the endplates are made of steel of 3 mm thickness and the paddles were made of galvanized steel sheets of thickness 2 mm. The overall dimensions of the suggested rotor are shown in **Figure 1**.

In all experiments, the main flow is produced by a 1.48 kilowatt-5 blades rotating blower of 1 m diameter and it is covered by a steel grid in order to generate uniform flow. It can provide a wind-like speed up to 14 m/s. Wind velocity is measured by Windmeter (Hand Held Anemometer) which provides the speed measurements in the range of 0.2-30 m/s with an accuracy of ±5%. The rotor is allowed to rotate from no load speed. The rotational speed of the rotor is recorded by a digital tachometer called Smart Sensor model AR925. The features of this type of tachometer are such that: speed range of 0.5 – 19999 RPM with an accuracy range of ±0. 05% and resolution of 0.1 RPM. We adapted the procedure used in [10] for measuring the static torque. This measuring system is called brake-drum instrumentation. It employs a portable digital scale HD-F01 of Huida with a capacity of 30 kilograms and minimum scale division of 10 grams. The rotor is loaded gradually to record spring balance reading, weights and rotational speed of the rotor. At a given wind velocity, the rotor is loaded to prevent it from rotation at a given rotor angle. The values of load and spring balance reading are recorded to calculate the static torque at a given rotor angle. This process is repeated several times for calculating the average torque value.

4. RESULTS AND DISCUSSIONS

A theoretical study is made to investigate the effects of the number of blades on the performance potentials of the proposed on-off blade rotor. Three different rotor design configurations which comprise 4, 8 and 16 blades are considered. The chosen numbers of blades make it possible to investigate the effects of duplicating the number of blades on the torque and power coefficients. According to the design criterion that is thoroughly presented in Section 2, with the height of all blades kept constant, doubling the number of blades means doubling the total height of the rotor. The theoretical study is performed on the basis of an experimental investigation which showed that the peak of the power coefficient which corresponds to a free stream velocity, U_∞ = 8 m/Sec, occurs at speed ratio λ = 0.6. This fact will be discussed later on.

The variations of mean values of the torque and power coefficients with the speed ratio, λ, at wind speeds of 8 m/Sec for the three different rotors with the rotor height duplicates as the number of blades duplicates is shown in **Figures 5** and **6**. Generally, as the number of blades increases the mean torque and the mean power coefficient increase. The generated torque (**Figure 5**) is going to be lower as the speed ratio increases, because of the reduction of the generated momentum force. The power coefficient (**Figure 6**) on the other hand has a 3rd degree curve with its peak located at the same value of speed ratio (λ = 0.6) and the peak value increases with increasing the number of blades.

The mean torque and the mean power coefficients against the variation of the speed ratio when doubling the number of blades with the heights of all rotors remain the same as the height of the 8-blade rotor is shown in **Figure 7** and **8**.

The height of blades in **Figure 7** and **8** for the 16-blades rotors were decreased to half the height of the 8-blade rotor and the heights of blades of the 4-blade rotor are increased to duplicate the height of the blade of the 8-blade rotor. It is interesting to see that there are not any variations of the mean torque for the three rotors (**Figure 7**), while the quantitative forms of the power coefficients of the different rotors remain as before in **Figure 8** when the height of rotors were different.

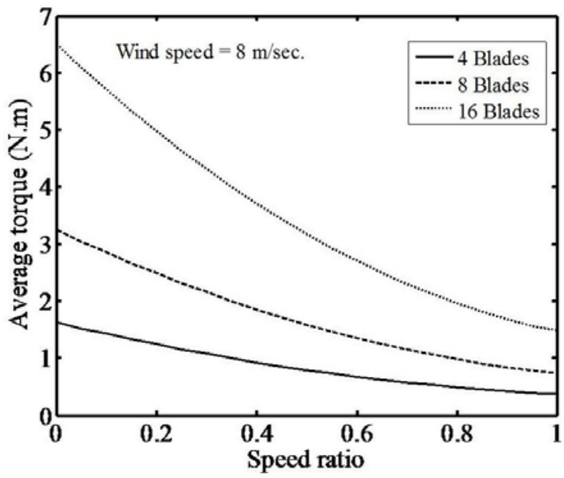

Figure 5 Torques for rotors of different heights.

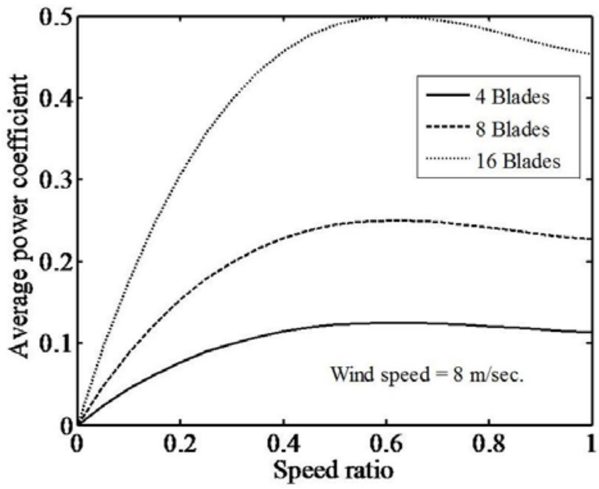

Figure 6 Power coefficients for rotors of different heights.

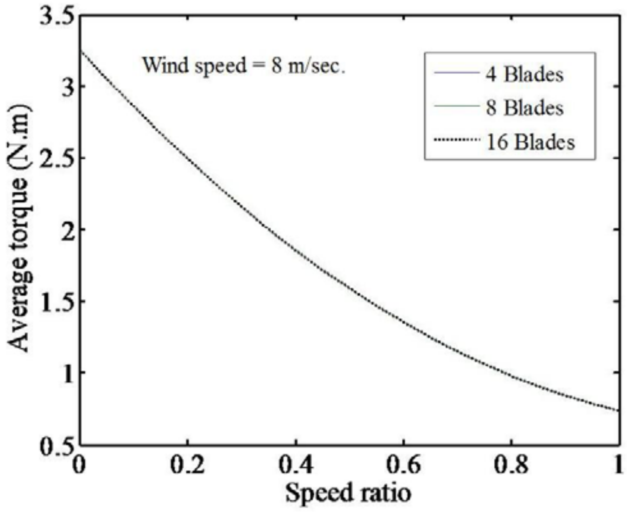

Figure 7 Torques for rotors of the same height.

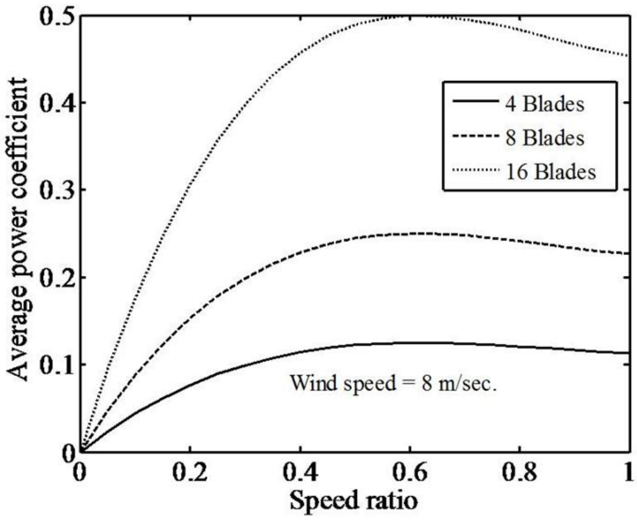

Figure 8 Power coefficients for rotors of the same height.

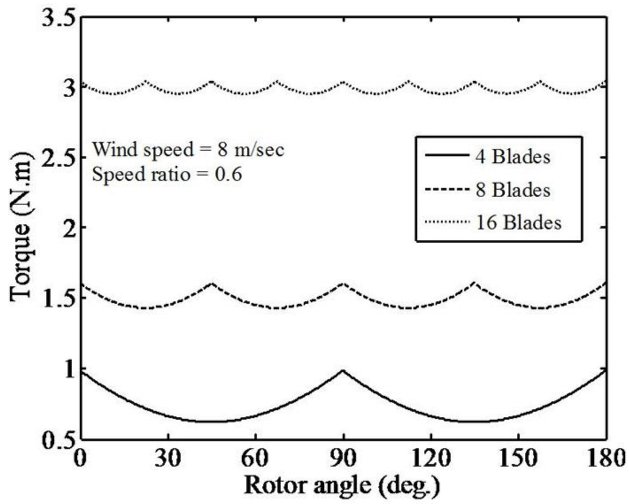

Figure 9 Torques for rotors of different heights.

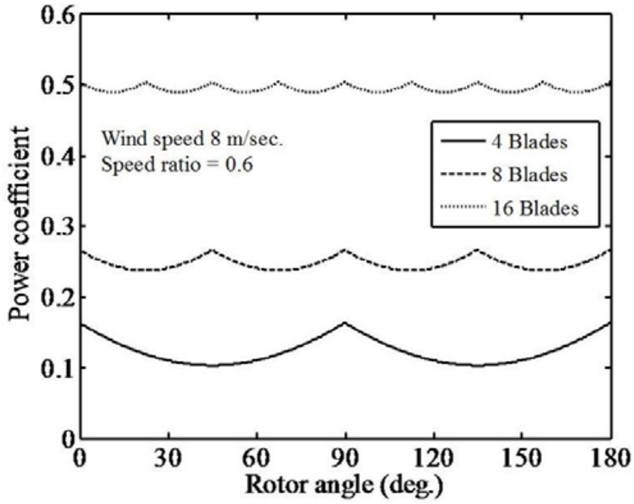

Figure 10 Power coefficients for rotors of different heights.

Now, we will investigate the effects of doubling the number of blades on variations of the generated torque and power coefficient against variations of the local positions of all active blades along the 180-degree active angle of operation. The results are shown in **Figures 9** and **10**. The fluctuations of the torque and hence the power are associated with variation of the imposed momentum force.

The motivation behind most total torque studies generated by different (steps) stages is related to the need for better understanding of the mechanisms which are responsible for inducing structural vibrations in vertical wind turbines. These vibrations can lead to radiated acoustical noise or structural damage if the oscillations are large. This issue will be of future research investigation of the current authors. From the angular position history of the torque and power coefficient in **Figures 9** and **10** increasing of blade stages leads to smoothening of the generated torque and power with noticeable reduction of the cycle period. The period can be estimated by measuring the angle between two neighboring peaks; this reads: 90, 45 and 22.5 degrees which are corresponding to the 4-, 8- and 16-blades rotors, respectively. It is also noticed from **Figures 9** and **10** that the mean generated torque and power coefficient are duplicated with duplication of the number of (steps) stages which duplicates the number of blades.

The same theoretical study is performed for the three rotors except that the overall heights of the three rotors are kept constant and all equal the height of the 8-blade rotor. It means that the heights of blades of the 16-blade rotor were decreased to half the height of the 8-blade rotor and the heights of blades of the 4-blade rotor is increased to duplicate the height of the blade of the 8-blade rotor. The results are plotted in **Figures 11** and **12**. It is noticed from this figure that the mean value of the torque is not affected by the variation of the number of blades as long as the overall heights of the rotors are the same. The behavior of the power coefficient does not vary when compared to **Figure 9** because, as was expected, the power

coefficient is a dimensionless value and will not be affected by the variations of blade height.

A theoretical and experimental comparison between the power coefficients of the proposed multi-step 8-blade rotor and that of the classical Savonius turbine are performed and the results are plotted in **Figure 13**. The experimental data for the Savonius turbine were adapted from [12]. It can be deduced from **Figure 13** that the proposed multi-step rotor can produce a higher power coefficient than that of Savonius turbine in the range of $\lambda \leq 0.7$ after which a strong drop of the power coefficient is clearly visible. This is due to the power lost in the mechanical vibration generated by the intensive rotation of the rotor. In view of the aerodynamic analysis, the high speed leads to a strong oscillated wake behind the blades causing also a large lost energy. It also notices that the theoretical analysis is proven to be effective in describing the performance of the proposed multi-step and Savonius rotors for a range of speed ratio $\lambda \leq 0.6$ for the proposed multi-layered rotor and a range of speed ratio $\lambda \leq 0.7$ for the Savonius rotor. This is due to the ideal flow theory considered in the present analysis.

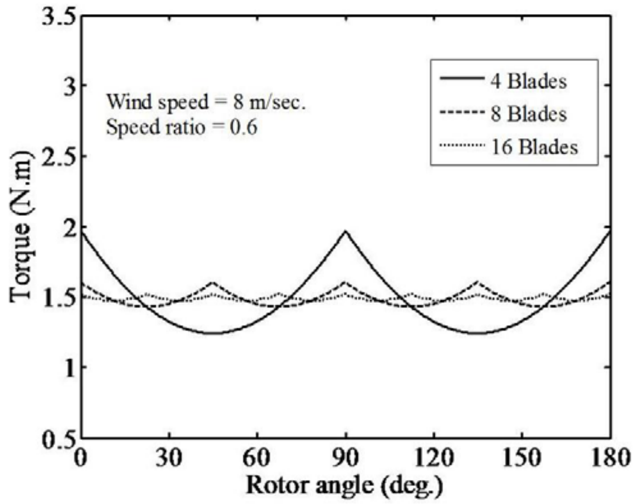

Figure 11 Torques for rotors of the same height.

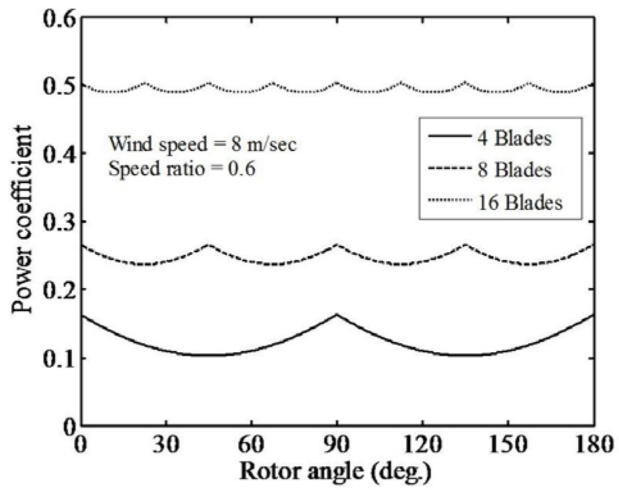

Figure 12 Power coefficient for rotors of the same height.

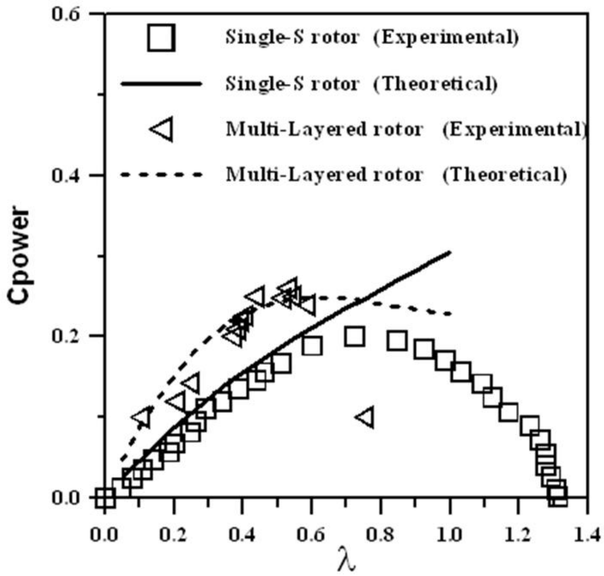

Figure 13 Comparing the proposed 8-blade rotor and the Savonius rotor.

5. CONCLUSIONS

A study is made to investigate the relative performance potentials of a newly designed oscillating-blade vertical wind turbine. It looks like a vertical tower of four (steps) stories where each story has a (lower endplate) circular floor and a (upper endplate) circular roof with two blades installed and aligned at a180-degree angle around the shaft of the rotor. The main advantage of such design is that there is no need for a special or complicated mechanism for opening and closing the blades. They automatically open and close by the action of the air flow with the aid of simple hinges and blade stops. Both theoretical and experimental investigations are performed and compared. The main interesting result which was justified theoretically and experimentally is that the maximum power coefficient of the proposed rotor takes place at a speed ratio of 0.6 with wind speed of 8 m/s. This makes the proposed rotor liable for application in a lot of areas around the world where the recorded average speed is around 8 m/s. It provides the power coefficient higher than that of the classical Savonius rotor while the latest offers wider speed ratios. Also, the Savonius rotor provides its maximum power coefficient, which is lower than that of the proposed rotor, at a higher speed ratio than that of the proposed rotor. The results of the theoretical investigations regarding the duplication of the number of blades, which consequently duplicates the height of the rotor, are very encouraging in terms of the offered power coefficients and generated torques.

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